Comparison of the 10×10 and the 8×6 Supersonic Wind Tunnels at the NASA Glenn Research Center for Low-Speed (Subsonic) Operation

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ABSTRACT

NASA Glenn Research Center and Lockheed Martin tested an aircraft model in two wind tunnels to compare low-speed (subsonic) flow characteristics. Test objectives were to determine and document similarities and uniqueness of the tunnels and to verify that the 10– by 10–Foot Supersonic Wind Tunnel (10×10 SWT) is a viable low-speed test facility when compared to the 8– by 6–Foot Supersonic Wind Tunnel (8×6 SWT). Conclusions are that the data from the two facilities compares very favorably and that the 10– by 10–Foot Supersonic Wind Tunnel at NASA Glenn Research Center is a viable low-speed wind tunnel.

ACRONYMS AND SYMBOLS

AOA	Angle of Attack
AOS	Angle of Side Slip
CDA	Concept Demonstration Aircraft
CFD	Computational Fluid Dynamics
CTOL	Conventional Take-off and Landing
DOE	Design of Experiment
JSF	Joint Strike Fighter
M	Mach Number
NASA	National Aeronautics and Space Administration
Re	Reynolds Number
STOVL	Short take-off and vertical landing
SWT	Supersonic Wind Tunnel

INTRODUCTION

When a wind tunnel test facility is chosen for a test, it is assumed that the results will be of high quality and will produce results similar to other facilities. At NASA's Glenn Research Center, two wind tunnels, the 8×6 SWT and the 10×10 SWT, were utilized to perform a comparison of data results in a subsonic flow range.

The subsonic comparison test was a joint effort by NASA and Lockheed Martin using a Lockheed Martin Joint Strike Fighter Concept Demonstration Aircraft (JSF CDA, X-35) as the test article. As a result of facility control system updates, the 10×10 SWT was re-introduced (1995) as a subsonic facility augmenting its supersonic capabilities. This test was used to verify the 10×10 SWT subsonic performance using the 8×6 SWT as the reference.

Although the 10×10 SWT and 8×6 SWT have many similarities, they also have unique characteristics. Therefore, test data were collected in both facilities for multiple model configurations at various vertical locations in the test section, starting at the test section centerline and extending into the ceiling and floor boundary layers.

Stated test objectives were as follows:

1. Verify the 10×10 SWT is a viable subsonic test facility for the core flow area of test section based on comparison to the 8×6 SWT.

2. Identify core flow characteristics of the 10×10 SWT by comparing model data of the 10×10 SWT versus the 8×6 SWT at multiple low-speed conditions and model positions.

3. Determine the range of motion of the model allowed in each tunnel to prevent boundary layer ingestion into the lift fan or main engine inlets.

The purpose of this report is to provide an overview of the data comparison results and state conclusions. In addition, the report includes tunnel descriptions, tunnel history, and references to calibration tests that were recently performed at both tunnels.

DESCRIPTION OF FACILITIES

10×10 SWT DESCRIPTION

The 10×10 Foot Supersonic Wind Tunnel is NASA's largest continuous high-speed (Mach > 2) propulsion wind tunnel. Operational capabilities of the 10×10 SWT subsonically vary from near static conditions to Mach 0.36 (240 knots) and supersonically from Mach 2.0 to 3.5. See the summary in figure 1.

The tunnel is a continuous flow wind tunnel that can be operated in either an aerodynamic (closed loop) or propulsion (open loop) cycle. The tunnel has variable density capability to permit simulation of altitude and/or Reynolds number ranges.

For complete information on the 10×10 Supersonic Wind Tunnel, refer to the user manual.[1]

8×6 SWT DESCRIPTION

The 8×6 Foot Supersonic Wind Tunnel is part of the 8×6 Foot Supersonic/9×15 Foot Low-Speed Wind Tunnel Complex where two test sections are housed in the same tunnel loop. Operational capabilities of the 8×6 SWT vary from near static conditions, Mach 0.02 to 0.09 (14 to 60 knots) and Mach 0.25 (165 knots) up to Mach 2. See summary in figure 1.

The tunnel complex is an atmospheric pressure, continuous flow wind tunnel that can be operated in either an aerodynamic (closed loop) or propulsion (open loop) cycle. The 8×6 SWT has the capability to bleed off and reduce the boundary layer with a system that exhausts air through the test section porous walls. For complete information on the 8×6 Supersonic Wind Tunnel refer to the user manual.[2]

TUNNEL COMPARISON

The tunnels were built at about the same time during the late forties/early fifties and have similar mechanical systems for creating and controlling airflow. Both tunnels have been updated with nearly identical operating controls and electronic systems including data collecting hardware and software. The new control systems have allowed for expanded operating capability of each tunnel including subsonic operation of the 10×10 SWT.

Setting the tunnel airflow velocity for subsonic operation is similar in both tunnels. For each tunnel velocity, a specified compressor speed is set. The supersonic flex wall is set the same for all subsonic conditions and the second throat doors are set to a designated position. Fine-tuning of velocity is accomplished at the 10×10 SWT by adjusting blocker doors just downstream of test section while fine-tuning in the 8×6 SWT is accomplished by adjusting test section plenum pressure. See figures 2(a) and 2(b) for schematics of each wind tunnel.

Three main differences between the tunnels are 1) the subsonic speed range 2) the 8×6 SWT test section is a porous wall design while the 10×10 SWT has solid walls 3) the 10×10 SWT can obtain specific Reynolds numbers by varying the air density while the 8×6 SWT is an atmospheric facility.

PREVIOUS CALIBRATION TESTS

Tests were performed in 1995 for the 8×6 SWT and in 1996 and 1998 for the 10×10 SWT to calibrate the tunnels at their designated subsonic operating conditions. Specially designed rakes and instrumentation were used to map and gather information. Detailed reports of these calibration tests[3-5] show specific characteristics of each tunnel's flow fields.

Highlights and conclusions of the calibration efforts for both tunnels are as follows:

- Based on the boundary layer thickness, the usable test section area for the 10×10 SWT is 6 by 6 foot and for the 8×6 SWT is 7 by 5 foot.
- Calibration curves relating facility instrumentation measurements to test section flow characteristics were created to provide an accurate means of setting operating conditions.
- Reference tables were created to allow operators to repeat conditions for future subsonic tests.
- Reports provide graphs showing spacial variation in pressure, Mach number, flow angle and spanwise turbulence.
- Reports concluded that both tunnels have good quality airflow at advertised subsonic speeds.

TEST HARDWARE AND INSTRUMENTATION

The Lockheed Martin Joint Strike Fighter Concept Demonstration Aircraft (JSF CDA, X-35) 0.11554 scale model was used in both tunnels. See figure 2C. The model was instrumented with steady state and dynamic (high response) total pressure transducers across both the main engine and lift fan inlets. In addition, steady state static taps were located in the main engine inlet throat and auxiliary main engine inlet.

Facility controlled exhaust system hardware and instrumentation was utilized to create (simulate) and measure main engine and lift fan inlet airflow. A five-hole flow angularity probe was traversed from the tunnel ceiling to measure boundary layer flow conditions.

The standard existing facility electronics and instrumentation for both tunnels were utilized during the tests to document tunnel operating conditions. Steady state data were gathered in both tunnels using an electronically scanned pressure (ESP) system in conjunction with a real time data acquisition and display system. High response data were gathered using the facility dynamic data system. Tunnel instrumentation included multiple bellmouth total pressure taps, ceiling static pressure taps from the bellmouth through the test section, a hygrometer for dew point measurement and total temperature thermocouples. The test matrix sequencer (TMS) system was utilized to automate all model functions and movements for expediting test matrix sequencing.

TEST PLAN

The approach was to obtain subsonic data in the 8×6 SWT and 10×10 SWT facilities using the Lockheed Martin Joint Strike Fighter (JSF) model configured identically in both tunnels. Data were taken at the same tunnel velocities in both facilities and at some velocities only obtainable in each tunnel. The first phase of the test was to maneuver the model through multiple positions of angle of attack and angle of sideslip at the test sections core flow area. The second phase of the test was to move the model toward the ceiling or floor (tunnel height sweeps) to see the effects on the data when the model approaches the boundary layer. Both phases were conducted in both the STOVL (Short take off vertical landing – Lift fan in operation) and CTOL (Conventional takeoff and landing) configurations. Mass flows through the lift fan and main engine ducts were set at each condition as specified by the test matrix. Also, during the tunnel height sweeps toward the ceiling, a five-hole flow angularity probe was utilized to measure boundary layer total pressure at multiple distances from the ceiling while the model entered the boundary layer.

Additional data were obtained in the 8×6 SWT during tunnel height sweeps by shutting off the test section bleed system to observe the impact of the boundary layer bleed on tunnel/model performance.

MEASUREMENT ACCURACY

Pressure recovery is the main parameter that is evaluated when comparing the tunnels. The pressure recovery is affected by the model configurations and tunnel conditions that are set in each tunnel; therefore repeatability of conditions between tunnels is critical. The table below shows the estimated accuracy for the parameters and the resulting uncertainty of the pressure recovery. Pressure recovery measurement uncertainty is ±0.0045 or about 0.5% for either tunnel. This analysis does not take into account the uncertainty of all measuring devices used for the test except for the pressure measuring devices; so actual data uncertainty may be higher.

Parameter	+/- Accuracy	+/- Pressure Recovery
Tunnel Velocity	2.0 knots	0.0012
Angle of Attack	0.5 degrees	0.00135
Angle of Slip	0.5 degrees	0.0005
Lift Fan Flow	1.0 %	0.0007
Main Eng. Flow	1.0 %	0.0007
Pressure Measuring Device	0.005 psi - PT	0.0007
	0.005 psi - PTO	
Lift Fan Pressure Recovery Uncertainty		0.0045 or ~ 0.5%

DISCUSSION OF RESULTS

Pressure recovery in the lift fan and main engine inlet were the parameters compared between each wind tunnel test. Since pressure levels in each tunnel vary slightly due to different atmospheric conditions, pressure recovery was used as a normalized parameter to compare between tunnels.

The main engine and lift fan pressure recovery are defined as:
PT2PT0 – Average main engine pressure recovery
= PT2/PT0 – calculated using the area average of the total pressure probes at main engine aerodynamic interface plane (PT2), then dividing this average by the freestream total pressure (PTO).
PT2PT0LF – Average lift fan pressure recovery
= PT2LF/PT0 - calculated using the area average of the total pressure probes at lift fan aerodynamic interface plane (PT2LF), then dividing this average by the freestream total pressure (PTO).

Note: Complete disclosure of exact data and detailed description of model hardware is limited due to proprietary reasons. Objectives of the tests and this paper are not compromised by these omissions.

Figures 3 to 6 compare the average lift fan pressure recovery versus lift fan flows at four different tunnel/model conditions. All four plots show the airflow characteristics of the wind tunnels compare very well at each condition, well within the measurement uncertainty of the pressure recovery, with figures 5 and 6 showing the best case and worst case results, respectively. Figures 7 to 10 compare pressure recovery readings across the lift fan at the same tunnel/model conditions as figures 3 to 6. These plots show how both wind tunnels produce nearly exact trends and results, with some exceptions, for each point of measurement in the lift fan. Figures 11 to 14 compare the average main engine pressure recovery when the model is in the CTOL configuration and at four different tunnel/model conditions. Figures 15 and 16 compare pressure recovery readings across the main engine at the same tunnel/model conditions as figures 13 and 14. Again, the results show a close trend of data with all results within the uncertainty of measurement with the exception of the 240 knots and 25 degree angle of attack. At this condition the trend is close but some of data points are just outside the acceptable uncertainty that is a result of the repeatability of the parameters between tunnels.

The second phase of the test consisted of moving the model within the boundary layer of the floor and ceiling of the tunnels at 165 and 240 knots. This would determine the range of motion of the model allowed to prevent boundary layer ingestion into the lift fan or main engine inlets.

Figures 17(a) and 17(b) plot pressure recovery across the lift fan when the model nose is moved from outside to inside the known boundary layer of the each tunnel. Looking at each tunnel individually, pressure recovery is higher at some points around the lift fan but lower at some points thereby not indicating a significant trend when model nose is inside the boundary layer. Comparing tunnels shows consistent trends at the same points around the lift fan. Average pressure recovery of the lift fan increased slightly in the 8×6 SWT when the model neared the ceiling while there was no significant change in the 10×10 SWT under the same conditions as indicated by figure 18. None of the above mentioned changes in data are larger than the uncertainty of measurement so no real effects of boundary layer interaction can be concluded. Note that the boundary layer thickness in the 8×6 SWT is

approximately 6 inches and in the 10×10 SWT is approximately 16 inches.

Figures 19(a) and 19(b) plot pressure recovery across the main engine when the model is in the CTOL configuration and is moved toward the tunnel floor into the boundary layer of each tunnel. Figure 20 plots the average main engine pressure recovery versus model nose distance from each tunnel floor at multiple main engine flows. Again, as with the STOVL configuration, there are no overwhelming effects in data when the model nose enters the boundary layer for either wind tunnel. Note that nose of the model is approximately 6 inches closer to the boundary layer than both the lift fan and main engine inlets.

Ceiling boundary layer profiles were measured at each tunnel and are illustrated in figures 21 and 22. Profile results were consistent with the results found in previous calibration tests.

Lockheed Martin successfully employed Design of Experiments (DOE) method of test matrix reduction with the following specific results that are of significance to this paper:

- Average percent error in pressure recovery ranged from 0.3 to 0.9 % for DOE repeated data with higher tunnel velocities having higher error.
- Standard Deviations of the pressure recovery data for the repeated tunnel and model conditions tend to be on the same level or smaller (less variation) in the 10 ×10 SWT compared to the 8×6 SWT DOE data.
- Variation in test section conditions and model position was much smaller in the 10×10 SWT compared to the 8×6 SWT, except for corrected main engine and lift fan airflow, which had slightly higher variation in the 10×10 SWT.
- The smaller variation in the tunnel conditions in the 10×10 SWT facility could account for the smaller variation seen in the 10×10 SWT pressure recovery data.

Computational Fluid Dynamics (CFD) results conducted by Lockheed Martin generally agree with the test data.

SUMMARY AND CONCLUDING REMARKS

- Conclusions are that the 10×10 SWT is a viable facility (from the standpoint of data quality), in the speed range from 0 to 240 knots. The core flow is similar in size to the 8×6 SWT (7 by 5 foot) due to

existing boundary layers in the 10×10 SWT (6 by 6 foot) test section.

- Comparing 8×6 SWT and 10×10 SWT data shows results are within an acceptable range with most of the data within 1%.
- The boundary layer did not cause an apparent or significant change to data in either wind tunnel. However, the model was not moved very far into the boundary layer in the 10×10 SWT due to safety considerations. The solid wall test section of the 10×10 SWT is a disadvantage only that it shrinks the usable core flow. The 8×6 SWT test section boundary layer perforations expand the core flow and with exhaust suction on, creates even a better flow. There is little variation at the same conditions within the core flow of each tunnel.
- Design of Experiments method proved useful in planning test matrix and comparing the 8×6 SWT and 10×10 SWT operation and test results.

This test was a cooperative effort between NASA Glenn Research Center and Lockheed Martin where both parties would benefit from the testing. Lockheed Martin successfully evaluated several testing methods and model configurations, which included auxiliary model configurations, Design of Experiments (DOE) method for test matrix design, and new data reduction software, post-processing and database management programs. NASA verified with concurrence from Lockheed Martin that the 10x10 SWT is a viable low-speed wind tunnel and compares well with the 8×6 SWT.

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2. Soeder, R.H.: NASA Lewis 8– by 6–Foot Supersonic Wind Tunnel User Manual. NASA TM–105771, 1993.
3. Arrington, E.A.; Gonsalez, J.C.; Curry III, M.C.: Subsonic Calibration of the NASA Glenn Research Center 10– by 10–Foot Supersonic Wind Tunnel (1998 Tests), AIAA–2000–2448.
4. Arrington, E.A.; Gonsalez, J.C: Subsonic Flow Quality Surveys of the NASA Glenn Research Center 10– by 10–Foot Supersonic Wind Tunnel. NASA/CR—97-206326.
5. Arrington, E.A.; Gonsalez, J.C: Low Speed Calibration of the NASA Lewis Research Center 8– by 6–Foot Supersonic Wind Tunnel. NASA/CR—97-198527.
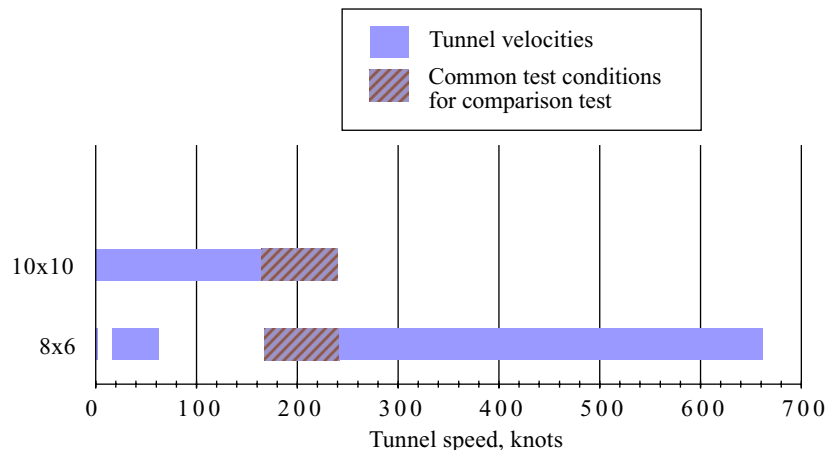
Figure 1.—Subsonic velocity capabilities for each wind tunnel with common velocities, as indicated, used in Comparison Test.

Figure not available.

Figure 2a.—Schematic of 10x10 SWT configured for subsonic flow.

Figure not available.

Figure 2b.—Schematic of 8x6 SWT configured for subsonic flow.
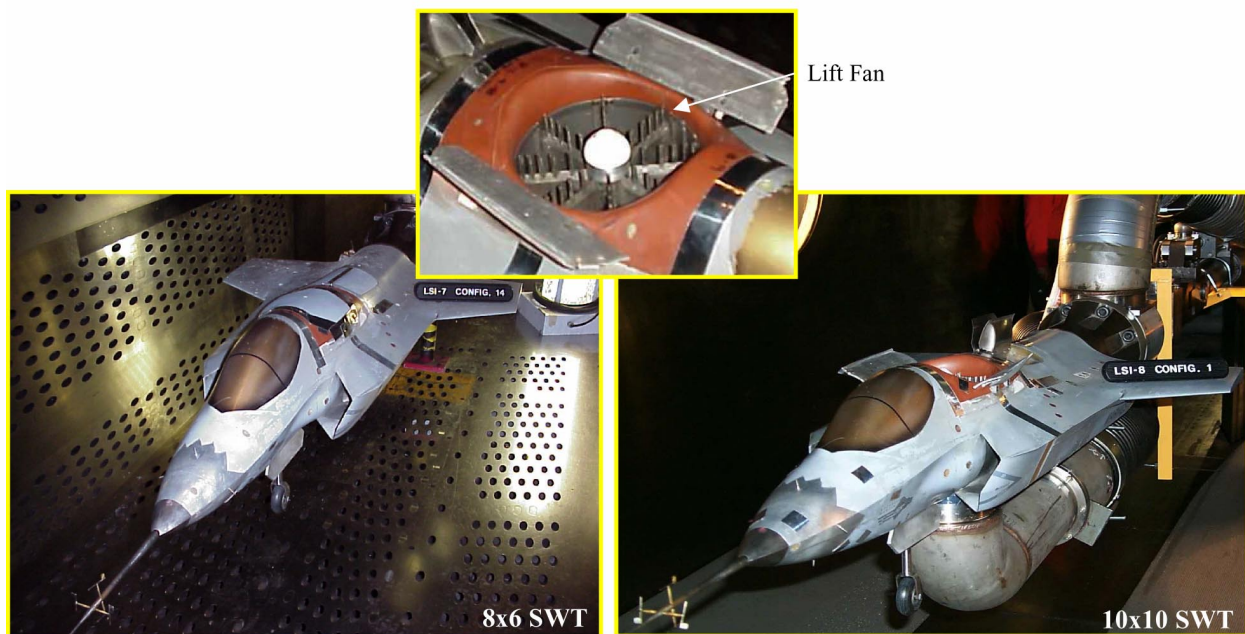

Lift Fan

8x6 SWT

10x10 SWT

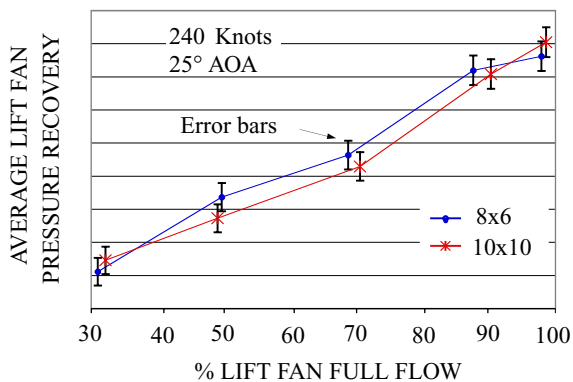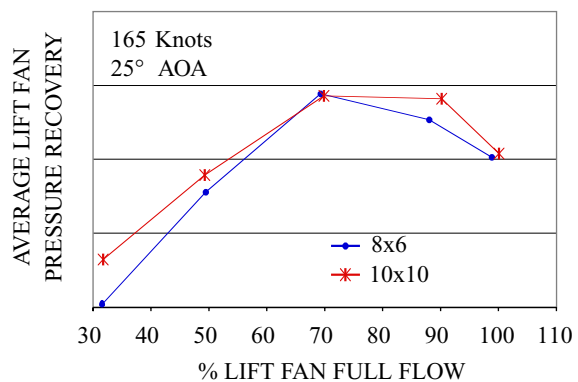Figure 2c.—Lockheed Martin Joint Strike Fighter model installed at Glenn Research Center.

Figure 3.—Pressure recovery data comparison for tunnel speed of 240 knots and model at 25° AOA. Y-axis horizontal lines are a 1% or 0.01 change in pressure recovery. Note uncertainty error bars.
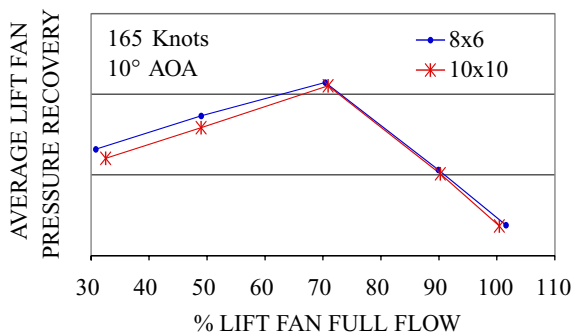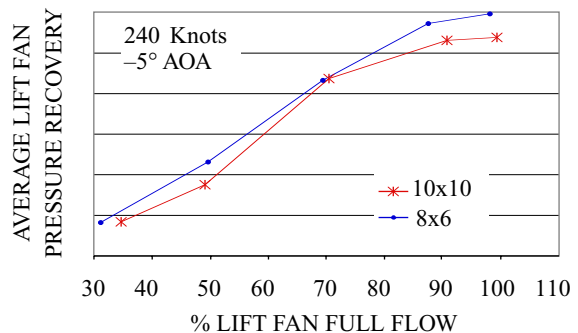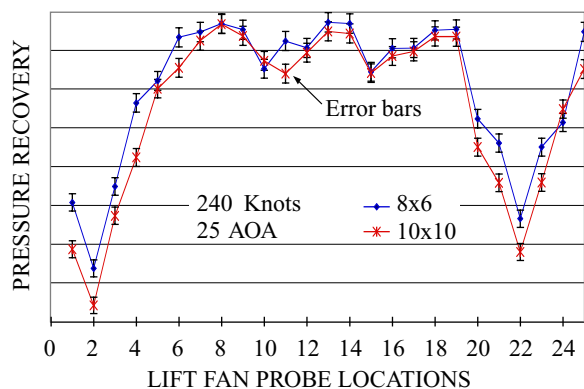

Figure 4.—Pressure recovery data comparison for tunnel speed of 165 knots and model at 25° AOA. Y-axis horizontal lines are a 1% or 0.01 change in pressure recovery.

Figure 5.—Best case results, pressure recovery data comparison for tunnel speed of 165 knots and model at 10° AOA. Y-axis horizontal lines are a 1% or 0.01 change in pressure recovery.

Figure 6.—Worst case results, pressure recovery data comparison for tunnel speed of 240 knots and model at −5° AOA. Y-axis horizontal lines are a 1% or 0.01 change in pressure recovery.

Figure 7.—Compares pressure recovery readings across lift fan for tunnel speed of 240 knots, 25° model AOA and 90% lift fan flow (ref. fig. 3) Y-axis horizontal lines are a 1% or 0.01 change in pressure recovery. Note uncertainty error bars.
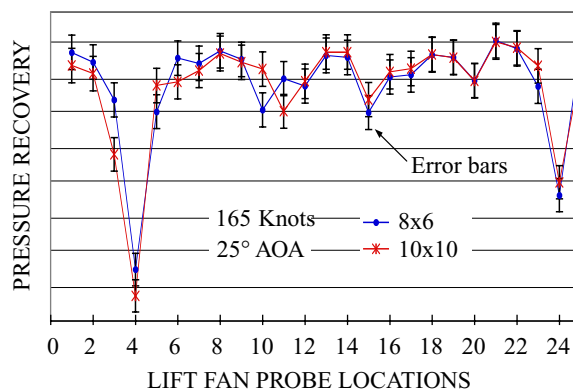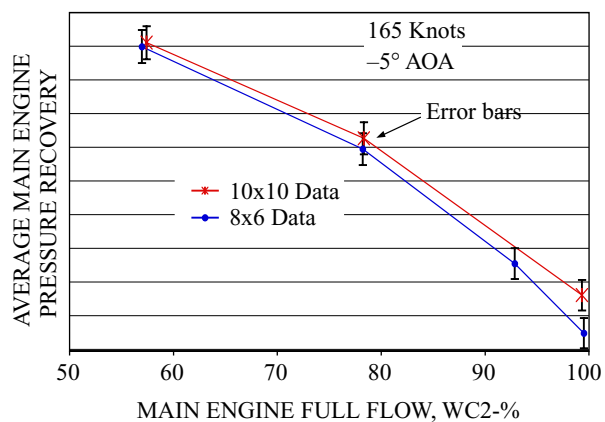

Figure 8.—Compares pressure recovery readings across lift fan for tunnel speed of 165 knots, 25° model AOA and 90% lift fan flow (ref. fig. 4) Y-axis horizontal lines are a 1% or 0.01 change in pressure recovery. Note uncertainty error bars.
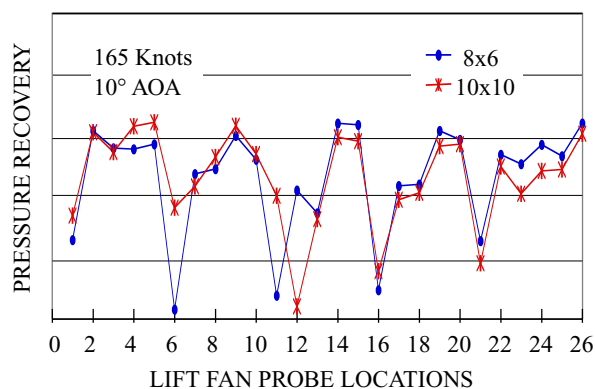
Figure 9.—Compares pressure recovery readings across lift fan for tunnel speed of 165 knots, –10° model AOA and 90% lift fan flow (ref. fig. 5) Y-axis horizontal lines are a 1% or 0.01 change in pressure recovery.
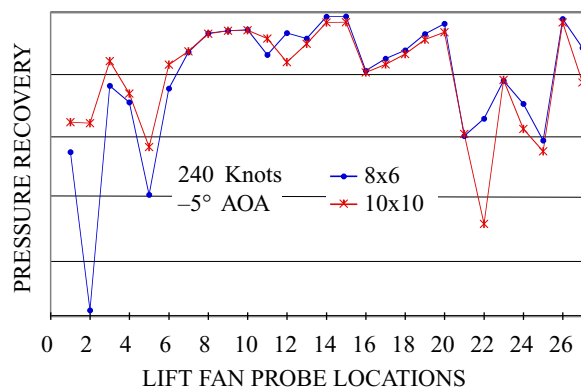
Figure 10.—Compares pressure recovery readings across lift fan for tunnel speed of 240 knots, –5° model AOA and 90% lift fan flow (ref. fig. 6) Y-axis horizontal lines are a 1% or 0.01 change in pressure recovery.
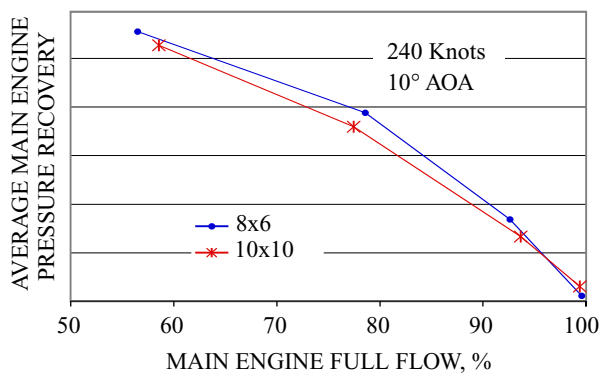
Figure 11.—In CTOL configuration, main engine pressure recovery data comparison for tunnel speed of 240 knots and 10° model AOA. Y-axis horizontal lines are a 1% or 0.01 change in pressure recovery.

Figure 12.—In CTOL configuration, main engine pressure recovery data comparison for tunnel speed of 165 knots and –5° model AOA. Y-axis horizontal lines are a 1% or 0.01 change in pressure recovery. Note uncertainty error bars.
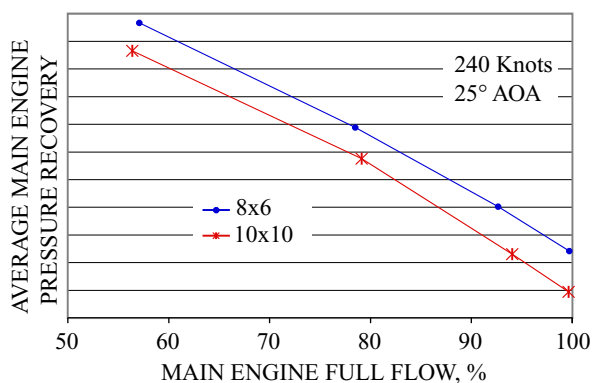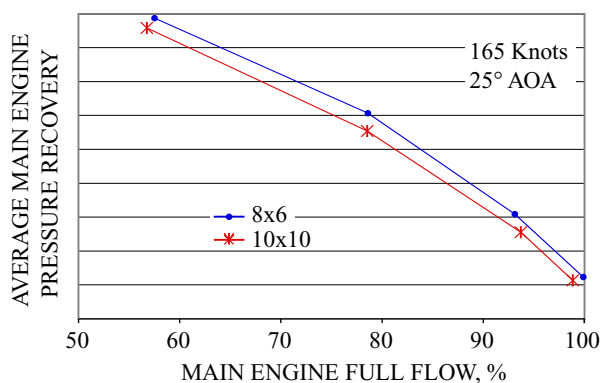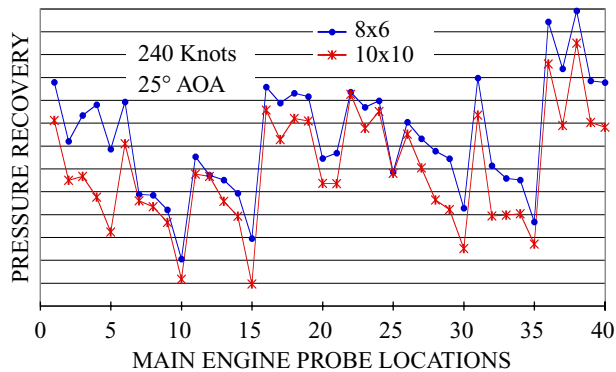

Figure 13.—In CTOL configuration, main engine pressure recovery data comparison for tunnel speed of 240 knots and 25° model AOA. Y-axis horizontal lines are a 1% or 0.01 change in pressure recovery.

Figure 14.—In CTOL configuration, main engine pressure recovery data comparison for tunnel speed of 165 knots and 25° model AOA. Y-axis horizontal lines are a 1% or 0.01 change in pressure recovery.

Figure 15.—In CTOL configuration, compares pressure
recovery readings across main engine for tunnel speed
of 240 knots, 25° model AOA and 100% main engine
flow (ref. fig. 13). Y-axis horizontal lines are a 1% or
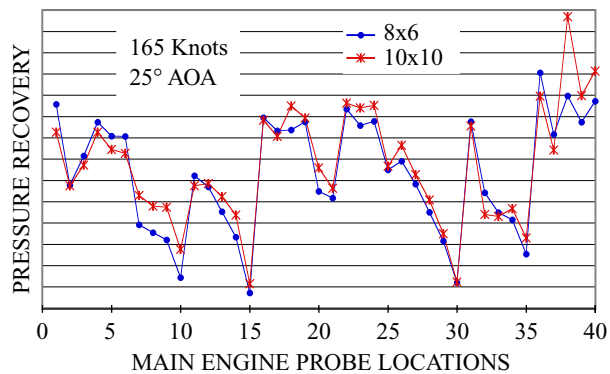0.01 change in pressure recovery.

Figure 16.—In CTOL configuration, compares pressure
recovery readings across main engine for 165 knots,
25° AOA and 100% main engine flow (ref. fig. 14).
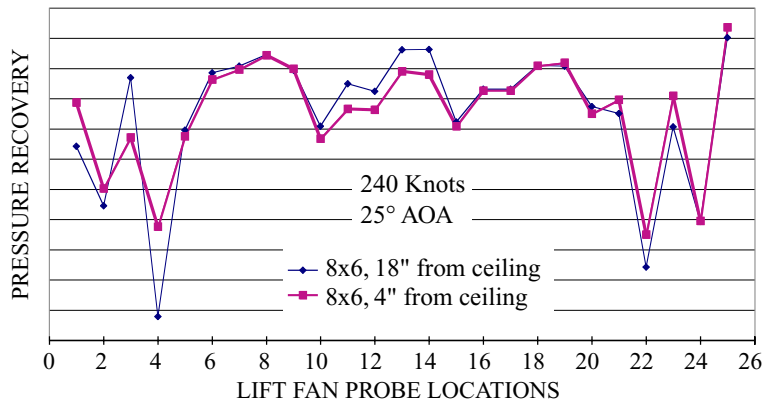Y-axis horizontal lines are a 1% or 0.01 change in
pressure recovery.

Figure 17a.—In the 8x6 SWT, comparing effects on lift fan pressure recovery when moving model from outside to inside the tunnel boundary layer for tunnel speed of 240 knots, 25° model AOA and 100% lift fan flow. Y-axis horizontal lines are a 1% or 0.01 change in pressure recovery.
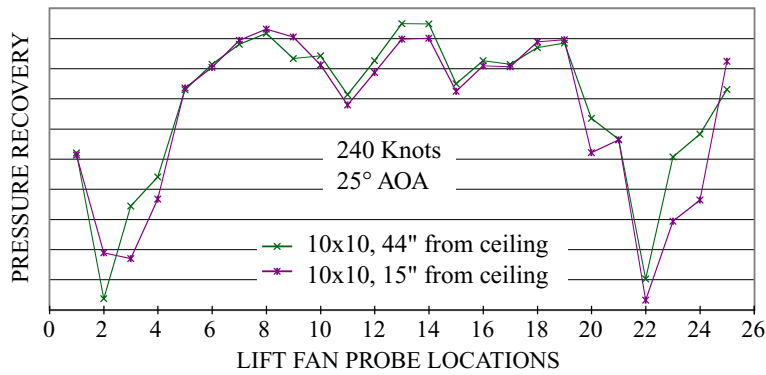

Figure 17b.—In the 10x10 SWT, comparing effects on lift fan pressure recovery when moving model from outside to inside the tunnel boundary layer for tunnel speed of 240 knots, 25° model AOA and 100% lift fan flow. Y-axis horizontal lines are a % or 0.01 change in pressure recovery.
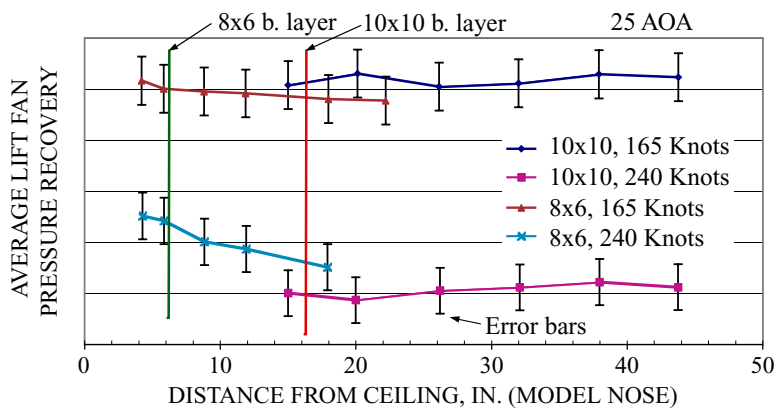

Figure 18.—Comparing the average lift fan pressure recovery when moving model from outside to inside the tunnel boundary layer for tunnel speeds of 165 and 240 knots, 25° model AOA and 100% lift fan flow. Y-axis horizontal lines are a 1% or 0.01 change in pressure recovery. Note uncertainty error bars. Vertical lines indicate tunnel boundary layer for 10x10 SWT and 8x6 SWT.
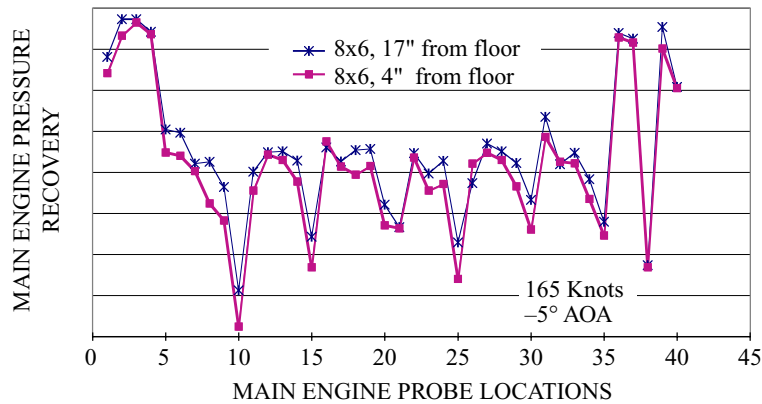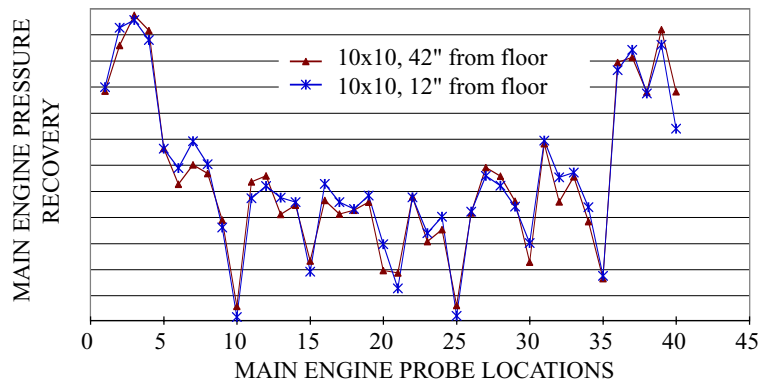
Figure 19a.—In the 8x6 SWT, comparing the effects on main engine pressure recovery when moving model from outside to inside the tunnel boundary layer for tunnel speed of 165 knots, –5° model AOA and 100% lift fan flow (CTOL configuration). Y-axis horizontal lines are a 1% or 0.01 change in pressure recovery.

Figure19b.—In the 10x10 SWT, comparing the effects on main engine pressure recovery when moving model from outside to inside the tunnel boundary layer for tunnels speed of 165 knots, –5° model AOA and 100% lift fan flow (CTOL configuration). Y-axis horizontal lines are a 1% or 0.01 change in pressure recovery.
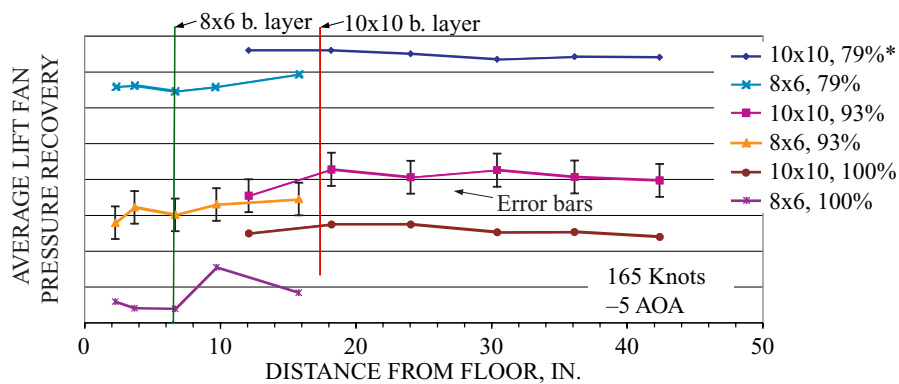

Figure 20.—Comparing the average main engine pressure recovery when moving model to inside the tunnel boundary layer for tunnel speed of 165 knots, –5° model AOA and *multiple main engine flows. Y-axis horizontal lines are a 1% or 0.01 change in pressure recovery. Note uncertainty error bars. Vertical lines indicate tunnel boundary layer for 10x10 and 8x6.
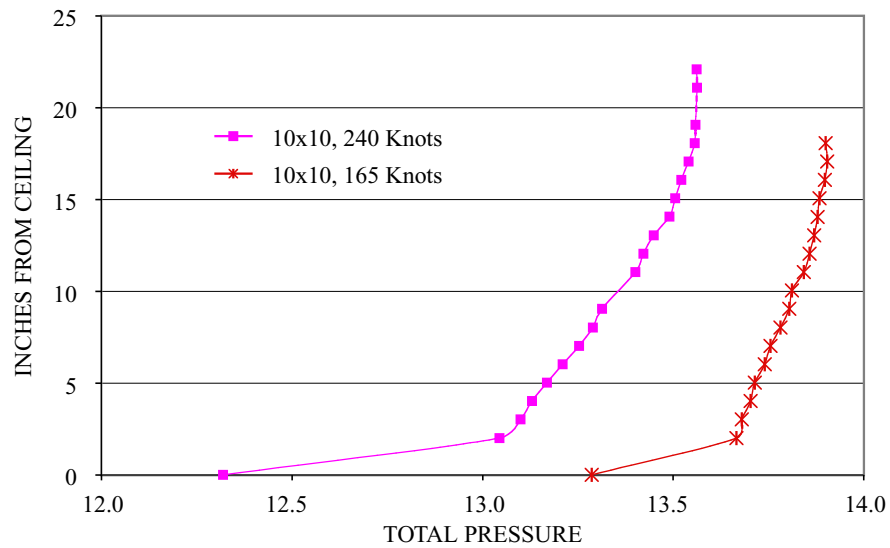
Figure 21.—Boundary layer profile of 10x10 SWT for tunnel speeds of 240 and 165 knots shows boundary layer thickness. Note: Reading at 0 inches is a tunnel wall static.
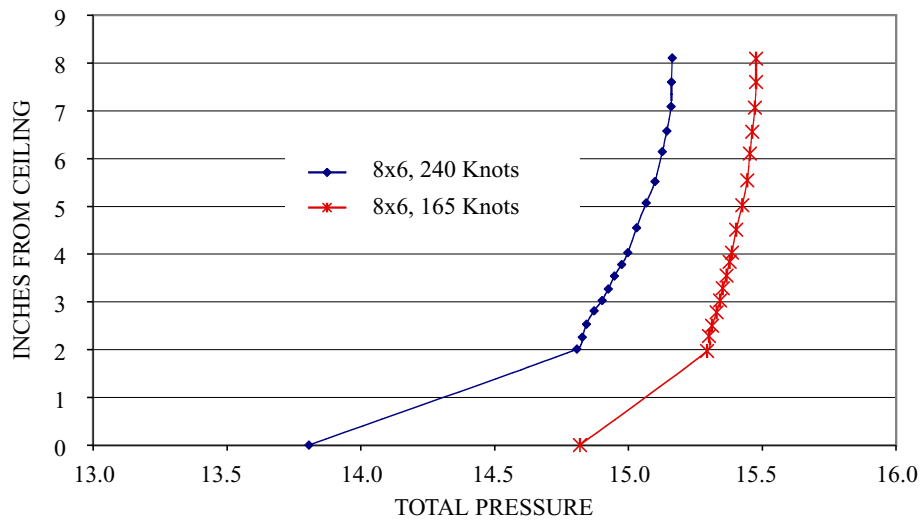

Figure 22.—Boundary layer profile of 8x6 SWT for tunnel speeds of 240 and 165 knots shows boundary layer thickness. Note: Reading at 0 inches is a tunnel wall static.

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NASA Glenn Research Center and Lockheed Martin tested an aircraft model in two wind tunnels to compare low-speed (subsonic) flow characteristics. Test objectives were to determine and document similarities and uniqueness of the tunnels and to verify that the 10– by 10–Foot Supersonic Wind Tunnel (10×10 SWT) is a viable low-speed test facility when compared to the 8– by 6–Foot Supersonic Wind Tunnel (8×6 SWT). Conclusions are that the data from the two facilities compares very favorably and that the 10– by 10–Foot Supersonic Wind Tunnel at NASA Glenn Research Center is a viable low-speed wind tunnel.

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